Role of morphology on two dimensional magnetic self-assembly

Miyashita, Shuhei ; Göldi, Maurice ; Nakajima, Kohei

Abstract: Self-assembly is a phenomenon broadly observed in nature where a vast number of various molecules spontaneously synthesize complex structures. In this paper, aiming at realizing highly autonomous self-assembly systems, we discuss fundamental issues attributed to self-assembly systems that employ magnetism as a driving force. We first introduce some examples from our case studies, in which the models all subscribe to a distributed approach, and thus lack central control. Then we categorize them by their type of magnet attachment. The discussed issues include several fundamental properties, such as the effect of morphology, stochasticity, the difference between 2D models vs. 3D models, emergence, allostericity, and parallelism. The obtained conclusions support our stance, which is that the appropriate morphology lightens the control cost for the assembly, providing primal but engaging instances of magnetic self-assembly systems that warrant further study.

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Kohei Nakajima

Shuhei Miyashita

Role of Morphology on Two Dimensional Magnet-Driven Self-Assembly

Shuhei Miyashita
NanoRobotics Lab.
Department of Mechanical Engineering
Carnegie Mellon University
Email: shuheim@andrew.cmu.edu

Maurice Göldi
and Kohei Nakajima
Artificial Intelligence Laboratory
Department of Informatics
University of Zurich

***Abstract*—Self-assembly is a phenomenon broadly observed in nature where a vast number of various molecules spontaneously synthesize complex structures. In this paper, aiming at realizing highly autonomous self-assembly systems, we discuss fundamental issues attributed to self-assembly systems that employ magnetism as a driving force. We first introduce some examples from our case studies, in which the models all subscribe to a distributed approach, and thus lack central control. Then we categorize them by their type of magnet attachment. The discussed issues include several fundamental properties, such as the effect of morphology, stochasticity, the difference between 2D models vs. 3D models, emergence, allostericity, and parallelism. The obtained conclusions support our stance, which is that the appropriate morphology lightens the control cost for the assembly, providing primal but engaging instances of magnetic self-assembly systems that warrant further study.**

***Keywords*—self-assembly, morphology, magnetism, embodiment, autonomous distributed system**

I. Experimental Setup

Self-assembly processes are normally realized in a distributed and stochastic manner, that is, once a set of experimental conditions is invoked, components act in parallel, intrinsically following local causal rules imposed by the system. Inspired by various instances that demonstrate self-assembly in nature, we have constructed an experimental platform to analytically investigate the properties of self-assembly [1], [2]. The platform was simple, but sufficient to study the relation of

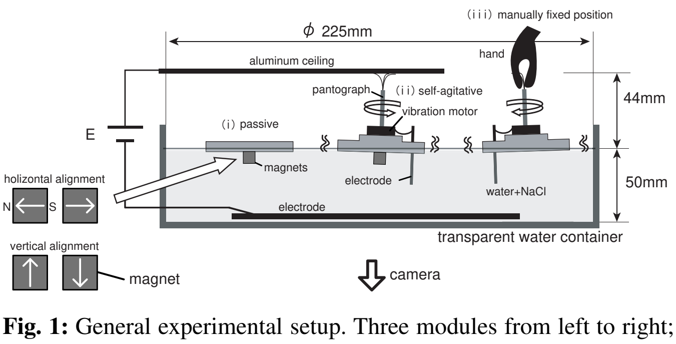

Fig. 1: General experimental setup. Three modules from left to right; passive, self-agitative, and manually constraint. Self-agitative module weighs $2.8\,g$ and has a footprint of $12.25\,cm^2$.

morphology, dynamics, and the product yield of a system. The experimental apparatus consisted of centimeter-sized floating modules, a water container, a pantograph mechanism, and a power supply. We prepared three types of modules: passive (Figure 1 (i)), self-agitative (Figure 1 (ii)), and manually fixed position (Figure 1 (iii)). All types had a single permanent magnet at the bottom for attaining attractive/repulsive interactions. The magnets were attached either horizontally or vertically, depending on the experiment (Figure 1 left-bottom illustration). Passive elements had no motors; they were simply floating tiles with an attached magnet. A self-agitative module and a manually handled module featured flat coreless vibration motors (FM34F, $12000 \sim 14000\,rpm\,(2.5-3.5\,V)$), which were directly attached on their bodies (Figure 1 photo). This allowed the modules to jiggle and rove around on the water. As a power supply for the modules with vibration motors, we opted to supply electricity through a pantograph that drew current from a metallic ceiling (Figure 1). When voltage (E) was applied to the ceiling plate, current flowed through the pantograph to the vibration motor on a module, returning to ground via electrodes immersed in the conductive water (NaCl solution, $83.3\,g/l$). This mechanism enabled all the (ii) and (iii) type modules to acquire the same voltage.

II. Classification of Assembly Patterns

This section presents the assembly patterns formed by differently shaped modules. The observed behaviors are shown in Figure 2 and Figure 3, in which the magnets are horizontally attached (in Figure 2), or vertically attached (in Figure 3). Some are powered via the ceiling plate (Figure 2 ,(b), (c), (d), Figure 3 (g)), while the others are powered through a wire being sustained by hand (Figure 3 (h), (i)), passive but externally agitated (Figure 3 (f)), or pure passive (Figure2 (a), Figure 3 (j), (k)). Note that these self-assembly processes occur without any centralized controls.

A. Horizontal magnetic alignment

In Figure 2, five aggregation patterns are presented in which the magnets are horizontally attached to the modules (see Figure 1). The initial and the final configurations are presented, respectively.

We classified the observed assembly patterns into two groups: namely, Linear alignment and Clustering, according to the topology created.

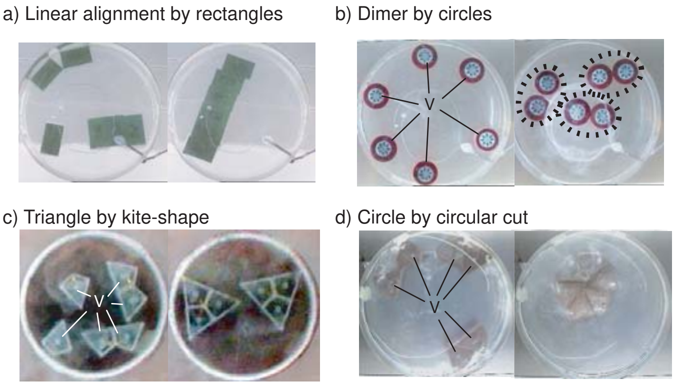

Fig. 2: The assembly patterns of different modules which are equipped with horizontally aligned magnets; linear alignment (a) [3], clustering (b-d) [1]–[3]. The modules containing vibration motors are indicated with the letter V The arrows in each illustration represent the way in which the magnets are attached.

- **Linear alignment:** A set of rectangular modules aligns into a straight configuration (Figure 2 (a))
- **Clustering:** Circular modules form dimers (Figure 2 (b)), Kite-shaped modules configure trimers (Figure 2 (c)), Six circular cut-shaped modules form a circle (Figure 2 (d)).

The system shows the characteristics of monopoles due to the arrangement of the magnets.

B. Vertical magnetic alignment

Figure 3 shows six assembly patterns that are obtained by attaching the magnet vertically to the modules' bottom surface.

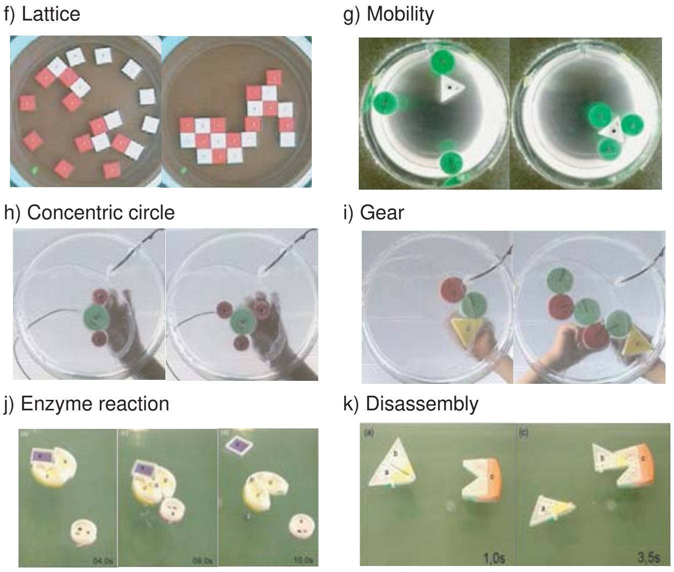

Fig. 3: The assembly patterns of modules with vertically aligned magnets. The modules containing vibration motors are indicated by the letter V Lattice by passive squares (f) [4], Mobility by vibrating triangle and circles (g) [5], Concentric circle by vibrating and passive circles (h) [3], Gear by vibrating triangle and circles (i) [3], Logical enzyme reaction (j) [6], Disassembly by passive third module (k) [6].

In each example, a schematic is presented with the orientation of the magnets' attachment, and the initial and final configurations with snapshots. The assembly patterns are classified into two folds: alternate positioning and logical reaction.

- **Alternate positioning:** Passive square modules form lattice structures (Figure 3 (f)), Vibrating triangular module and circular modules induce translative wheeling action (Figure 3 (g)), Vibrating and passive circles configure a concentric circle (Figure 3 (h)), A simple gear system is created by a vibrating triangle and passive circles (Figure 3 (i)).
- **Logical reaction** Logical enzyme reactions can be realized by passive modules (Figure 3 (j)), A third module can cause disassembly (Figure 3 (k)).

These assemblies show the characteristics of dipoles, and the representative assembly patterns are alternate positioning.

C. Properties

Table I lists the properties attributed to the particular configurations shown in Figure 2 and Figure 3, respectively.

1) **Product.** The obtained products can be categorized into two groups: those that are open to further growth (polymer) and those that are closed (clusters). The possibility for further growth corresponds to the states of magnetic fluxes. Basically, polymers, lattices, and concentric circles are capable of proceeding to grow as long as additional modules are supplied; dimers, trimers, and hexamers are constrained from developing further.
2) **Magnetic flux.** Magnetic flux can be "closed" to the exterior by magnets filling up the space where the flux goes. Horizontal magnetic alignment and vertical magnetic alignment have different customs on flux capturing.
3) **Isometry.** Although the obtained assembly patterns are typical outcomes that we obtained with the described settings, this does not mean that these are the only outcomes possible with the given configurations.
4) **Functionality.** Some particular configurations show a correspondence between shape, behavior, and function. These functions are often obtained as emergent behaviors that are intrinsically comprised. Most of the assemblies show mere spacial patterning.
5) **Controllable parameter.** The interactions occur locally, although some global parameters exist, such as the level of agitation of the water container or the applied voltage. All these variables may give rise to different aggregation patterns.
6) **Dynamics.** Dynamically stable states show different characteristics from statically stable states. The formed structure can exist only by consuming energy and often shows robustness against external turbulence.
7) **Self-repair.** Homogeneous systems, such as biological organisms, commonly consist of homogeneous cells and thus feature redundant properties. The observed assembly processes and the configurations are typically robust against unforeseen damage, implying that the system could recover from failures and external disturbances to some degree (self-repairable).

TABLE I: Attributes of the systems shown in Figure 2 and Figure 3 a to l.

	Attachment	1) Product	2) Magnetic flux	3) Isometry	4) Functionality	5) Controllable parameter	6) Dynamics	7) Self-repair
(a)	vertical	linear polymer	open	none[a]	-	-	static	possible
(b)	vertical	dimer	closed	none	-	agitation magnitude	dynamic	possible
(c)	vertical	trimer	closed	(exist)[b]	-	agitation magnitude	dynamic	possible
(d)	vertical	hexamer	closed	(exist)[b]	-	agitation magnitude	dynamic	possible
(f)	horizontal	2D lattice	open	exist	-	-	static	possible
(g)	horizontal	concentric circle	open	(exist)[b]	mobility	translational speed	dynamic	possible
(h)	horizontal	concentric circle	open	(exist)[b]	-	rotational speed	dynamic	possible
(i)	horizontal	polymer	open	exist	torque transformation	transferred rotational speed	dynamic	possible
(j)	horizontal	-	open	-	Allostericity	-	static	difficult
(k)	horizontal	-	open	-	Allostericity	-	static	difficult

[a]strictly speaking isometry exists by facing the short edges side by side, but can be minimized by regulating the agitation level and the shape.
[b]if more modules exist

D. *Effect of Morphology*

In nature, morphology plays a crucial role in self-assembly systems. The presented demonstrations imply that an essential role is often played by the distribution of the body parts from the “origin of the force” (i.e., the magnets) rather than the overall geometry. A practical approach is to evaluate shape from an energetic perspective, and develop a scheme to ground the phenomenon in the context of physics. Figure 4 describes a geometry in which two components change absolute angles (θ_1, θ_2) keeping contact. The case shown is a generic instance of evaluating shape as a measure of the potential energy of the system (e.g., magnetic potential energy) by independently altering the variables (here, θ_1, θ_2), and deriving the system’s energy as a function. The “shape” of the derived function reflects the stability as well as the expectation of the system’s convergence. The shape of the components constrains the interaction, mainly due to the energetic stability of the components.

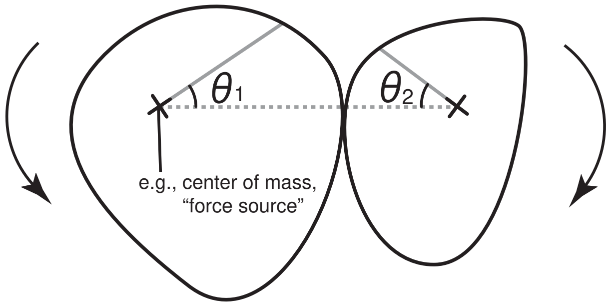

Fig. 4: Evaluation of shape by assessing the potential energy. By varying the angles (θ_1 and θ_2), a function $f(\theta_1, \theta_2)$ can be derived.

Some complex control mechanisms can be integrated in morphological properties. Other attributes, like friction or weight, also need to be combined in a way that the system fulfills its tasks with as little central control as possible. Take the lattice assembly in Figure 3 (a) for example: The stability of the formed structures were intrinsically determined by the shape of the constitutive tiles. Rounded tiles induced a folding motion, which was hardly observed in sharp-cornered tiles, enabling the clusters to smoothly converge to further stable states.

It is also worth mentioning that bonding strength between modules is commonly reinforced by the component’s morphology. Desired bondings make use of shape matching in addition to magnetic pole matching to restrict the bonding condition.

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